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Good Practices for Rechargeable Lithium Metal Batteries

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Abstract: High-energy rechargeable lithium metal batteries have been intensively revisited in recent years. Since more researchers started to use pouch cell as the platform to study the fundamentals at relevant scales, safe testing and handling of lithium metal and high-energy lithium metal batteries have become critical. Cautions and safety procedures are needed when handling cycled pouch cells with pulverized lithium metal particles inside. From cell design, electrode preparation, cell fabrication to testing procedure, this work aims to discuss the possible root causes that may initiate cell internal short circuit and raise safety concerns. Safe transfer, disassembly and disposal of cycled Li metal pouch cells are also discussed. The insights provided in this article are applicable for the research on high-energy lithium-ion batteries as well and may inspire more safety strategies to accelerate research innovation by using large-format batteries as the testing vehicle and conduct the research safely.

1. Introduction

Rechargeable lithium metal batteries could potentially double the cell-level energy of state-of-the-art lithium-ion batteries (LIBs).[1] It has been considered as one of the most promising next-generation battery technologies for electric vehicles with increased driving mileage and reduced cost. A tremendous effort has thereby been pursued to tackle the challenges of rechargeable lithium metal anode. It has now been gradually recognized that revisiting fundamentals underneath lithium metal anode at relevant scales is the first requisite to effectively validate novel concepts in this new battery technology.[2] New findings have been continuously reported when exploring the chemistry and electrochemistry in high-energy pouch cells,[3-7] providing many new insights to the community. Compared with coin cells, significantly more energy is now being packed into the restricted volume, e.g., pouch cell. More importantly, unlike LIBs, lithium metal anode in the lithium metal cell continuously breaks down into small particles, which may cause safety concerns if caution is not taken when handling lithium metals and the cells. Both the safety and lifespan of lithium metal batteries are rooted in the pulverization of Li metal.[4, 6] Although many solutions have been proposed to enable a stable cycling of lithium metal anode, much less attention has been paid to mitigating the safety risks of doing research on high-energy cells (lithium ion or lithium metal cells). Note that internal short circuit caused by Li dendrite is only one scenario of safety risk that can be effectively mitigated by controlling the deposition rate (charge rate) of Li anode.[8] Other possibilities coexist to induce cell short and thus thermal runaway during testing, cell transport and storage but have not been systematically studied for safe research purpose, although most of the risks can be effectively mitigated or eliminated if a safety plan is placed ahead.[9, 10]

In this work, we firstly analyze the possible causes that may generate safety concerns throughout the entire research period of high-energy lithium metal batteries. Based on the findings and understanding gathered at different steps, a detailed safety practice is proposed for the battery community. From the very beginning of cell design, electrode preparation, cell fabrication and testing to transfer, disassembly and disposal of cycled high-energy lithium metal cells, detailed safety practices have been developed at different stages. This work provides valuable information for doing research safely on high-energy cells and serves as a good resource for improving safe research environment for all non-aqueous battery technologies.

2. Common safety concerns when studying high-energy Li metal cells

Similar to LIBs, the main hazards contributing to the internal short circuit in Li metal batteries can be categorized into two types: 1) Physical contact between the cathode and anode, which usually arises from the material (defects on separators), manufacturing process (burr, particle, dust), and abuse conditions (heat, pressing, penetration, fall);[11, 12] 2) Contact between cathode and anode induced by chemical/electrochemical reactions, such as Li dendrite, iron impurity in cathode material, and current collector redistribution under abuse conditions, e.g., overcharge and overdischarge.[13-17] Without careful control, all these aforementioned scenarios may occur randomly throughout the research period of the high-energy batteries (not just Li metal batteries) and pose a safety concern. Figure 1 illustrates the simplified research cycle for Li metal pouch cells in the lab. During each research stage, there are different details from the experimental side that require attention to avoid unnecessary safety risks and minimize cell performance variations with baseline performance.

Intrinsically, the potential hazards that may show up in the high-energy lithium metal battery research process (Figure 1) are related to six aspects, namely, personnel, machine, material, method, measurement, and environment, which are summarized in Figure 2.[18] Most of possible reasons that lead to safety concern of working on high-energy battery can be found in Figure 2. In general, to improve the quality of Li metal pouch cells and mitigate safety concerns, the personnel who works on Li metal pouch cell should be trained and made aware of the safety plan and understand the critical failure pathways and mitigation strategies. Equipment used to produce, test, and disassemble Li metal pouch cells should be in good condition, with the required precision,[19] and with regular maintenance. Materials used for assembly of Li metal pouch cells need to be checked before use, e.g., no defects on the separator and controlled impurity level in the original material, etc.[20] Even from the beginning of cell design, safety parameters need to be included, such as the relative amount of Li metal and cathode or so-called N/P ratio, the alignment of electrodes and their relative dimensions.[21] When testing the Li metal pouch cell, test protocol, including the charging rate (Li deposition rate) and applied external pressure, should be considered and optimized in advance.[22] The environment also has impacts on cell testing. Li metal pouch cell needs to be prepared inside a glove box or inside a dry room with strict dust control. For example, the dry room we used to assemble the cell has a dew point below -50°C (0.1% relative humidity). The pouch cells need to be tested in a safety chamber filled by an inert gas. When transferring the cycled cell, avoid external force, e.g., drop, crush, vibration, or the vacuum to happen.[23] It is important to disassemble the cell in an Ar-filled glovebox (O_2, H_2O < 1 ppm) to minimize the risks and place all the disassembled cell components in mineral oil before further disposal.

3. Safety practices to handle Li metal pouch cells

3.1 Before cell test

Cell design: Similar to LIBs, cell design of Li metal pouch cells covers the information from materials selections on the cathode, Li anode, separator, binder, electrolyte, etc. to electrodes preparation, e.g., recipe, electrode dimension, coating quality, pressing density, porosity, and N/P ratio. Cell-level capacity and energy need to be balanced from the very beginning to enhance the safety attributes of the high-energy cell. Cell dimension, electrode overhang and even the tab position all require careful consideration.[24, 25] For lithium metal batteries, volumetric expansion and surface roughness are expected as a result of Li metal pulverization after extensive cycling.[6] The accumulated Li metal powders will continuously press against the separator.[14] For jelly-roll type cells, if Li agglomerates at the weak tensile strength direction of Celgard2500 (Table 1), the aggregated Li cluster may be "pushed" to penetrate through the separator membrane and short the cell. Therefore, the stress uniformity in jelly-roll type cells and appropriate selection of separators become critical. Figure 3 compares four typical types of Li-ion batteries manufacturing processes, including single sheet stacking, Z-stacking, cylindrical winding, and prismatic winding process.[11, 26] The most common process used by Asian battery manufacturers is prismatic winding, while European manufacturers prefer the single sheet stacking process. For single-sheet stacked cells (Figure 3a), the stacks of sheet separators and sheet electrodes are alternately stacked one on top of the other, the four edges of stacked cell without confinement increase the chances of cell shorting caused by Li deposition on the sides, whether it is Li-ion batteries or Li metal batteries. Z-stacking process (Figure 3b) generates less stress and enhance the uniform distribution of stress in the stacked cell. As Z-stacking process feeds the separator continuously in a z-style folding pattern while adding sheet electrodes in discrete location, only two sides (top and bottom) of stacked cell are open while the other two sides are wrapped by separators. Note that when applying Z-stacking process to fabricate Li metal pouch cells, sufficient distance (or overhang) between the separator and Li metal anode (2 mm for each side in the Li metal pouch cells in this work) should be maintained to reduce the chance of internal short circuit. The jelly roll from cylindrical winding (Figure 3c) and prismatic winding (Figure 3d) process usually has internal stress resulted from winding tension, tab, center pin (in the case of a cylindrical cell) and winding edge, which may induce cell deformation during repeated cycling.[27, 28]

Separators: While there is no commercial separator specifically designed for rechargeable lithium metal batteries, it plays an important role in enhancing the safety attributes of Li metal cells. Ultra-high molecular weight polyethylene (PE) membrane made by the wet stretch process possesses good tensile strength on both machine direction (MD) and transverse direction (TD). Propylene (PP) membrane and trilayer PP/PE/PP membrane made by the dry process usually have weak TD tensile strength (Table 1).[29, 30] Therefore, PE membrane is more resistant to the "attack" of Li agglomerates being accumulated during cell cycling. However, PE separator is more susceptible to thermal shrinkage than PP membrane if heat is generated. Ceramic coating greatly increases the thermal stability of PE separator (Table 1). When stacking electrodes manually, it is suggested that each tab of the electrode is attached to the separator simply by using a small piece of Kapton tape (See Figure 4 for details). This step will largely reduce the chance of misalignment between the cathode and Li anode. This step also ensures the safety of the disassembly process of a pouch cell and largely minimize the potential short that may occur because each electrode is fixed by the tape near the tab position.

Mixing and Coating: The mixing process and coating process are the core steps during the whole battery manufacturing process.[11] Precise control of electrode thickness and uniformity affects the safety of the Li metal pouch cells. For example, one common issue during mixing and coating process is the inhomogeneity of materials particles (Figure 5). This could be detected using a grindometer (Figure 5b). The grindometer consists of a steel block with a channel of varying depth. After pouring the slurry into the deep end of the groove and scraping it to the shallow end with a blade, irregularities will appear at the point where the groove depth is equal to the largest particle in the slurry. In Figure 5, although most of the NMC622 particles in the mixed slurry are under 45 μm (Figure 5a), a small number of agglomerated particles larger than 70 μm could still be detected (Figure 5c). Sometimes the diameter of the large particles exceeds 100 μm, which is even greater than the electrode thickness at ca. 70 μm. These large particles can act as a starting point to induce stress on the cathode and press against the separator. If the agglomerated Li also occurs in the vicinity of these stress points, the probability of severe self-discharge or internal short circuit during cycling is very high. Prior to coating, a filtration process is recommended to screen out large particles of the slurry, which will substantially improve the quality of coated electrodes.

Electrode cutting and "cleaning": The cutting process could easily yield particle "dusts" and burrs on the edges of the finished electrodes,[11] increasing the risk of direct contact between the cathode and Li anode. Especially for the stacked cells where more edges are present compared with wound cells, inspection and cleaning each edge of all electrodes are strongly suggested to minimize the risks caused by the cutting process. Figure 6a shows the burr on the edge of a cathode after cutting. In the center of the electrode is the Al foil with a thickness of ca.12 μm and NMC cathode are coated on both sides of the Al current collector. The size of the burr on the Al foil in Figure 6a is twice the thickness of Al foil. If the cutting process is completed using a scissor or a dull blade in the cutting die, the burr size becomes almost three times larger than the thickness of Al foil and approaching the electrode surface (Figure 6b). If the stress is generated during cell cycling, the burr may come into contact with the separator and eventually penetrate through the separator to short the cell. Periodical inspection on the blades used for cutting and the screen out electrodes with damaged edges will help decrease the probability of internal short circuit in Li metal pouch cells.

During the coating/drying process, due to the surface tension difference, slurry "travels" to the edges and increase the loading/thickness of active materials on the edges of the dried electrodes.[31] The "heavy edges" need to be cut out or they may deform and induce stress in the vicinity, leading to self-discharge and/or internal short circuit. The residual cathode is commonly seen in the tab area of the coated electrode (Figure 6c) and must be removed before cell assembly (Figure 6d). Otherwise, Li (stored in cathode) will be deposited on the anode edges directly facing this cathode "leftover" which may later propagate to the cathode side and short the cell. Similarly, during cell assembly, accurate alignment between cathode and anode is critical to ensure the maximum utilization of active materials as well as reducing the chance of internal short circuit.

Besides, inappropriate sealing of packing foil (aluminum-polymer laminated film), especially for top sealing where the tab extends, might cause leaking or short circuit. Optimization of the sealing parameters, including dwell time, temperature, and pressure is very important.[32] However, the sealing equipment commonly used in research labs may not have such functions of preciously controlling dwell time, temperature and pressure as in the industry, which makes the optimization of sealing process challenging. If cell-level energy is not a concern, a thick packaging foil is suggested to seal the cell. For example, a 155 μm thick packaging foil with an 80 μm thick polymer (cast polypropylene, CPP) layer coated on Al film reduces the risk of soft short due to the exposure of Al film beneath the polymer layer. High potential (Hi-pot) test is helpful to screen the short circuit between cathode and anode of a dry cell prior to filling the battery with electrolyte. By using this test at multiple points in the manufacturing process, defects such as particles or separator voids can be detected as early as possible.[33] Novel Li metal anode technologies to prevent dendrite formation help to reduce the opportunity of internal short circuit and is encouraged to be integrated into the fabrication of Li metal pouch cells if the novel Li metal anode is easy to mass-produce.[34]

3.2 During cell test

It is evident that high current density will induce the fast growth of dendritic Li which may short the cell, and ultimately leading to cell death.[35] Before an effective approach is adopted to completely eliminate the formation of detrimental Li dendrite, a low charging rate (e.g., C/10) is suggested to deposit Li metal slowly thus forming a relatively uniform Li layer to reduce the potential risks. However, after repeated cycling, lithium anode will still degrade due to side reactions between the electrolyte and lithium metal. It is suggested to use a stainless steel or aluminum alloy clamping device (Figure 7a) to apply the appropriate pressure to the pouch cell during testing and to facilitate the heat dissipation generated during discharge.[36] For lab testing of high-energy Li metal pouch cells, a safety chamber (Figure 7b) filled with inert gas with a venting system will greatly reduce the risks in case of any incidents. Additionally, overcharge/overdischarge protection is also needed during cell testing. In our testing program, set the protection voltage to be only 50 mV higher than the upper cutoff voltage or 110% state of charge (SOC), after which the cell will automatically stop charging. Additional cut-off parameters include cell and chamber temperature, time in step and pressure (if monitored). The similar protection mechanism needs to be applied for cell discharge process. It is worth mentioning that cells require at least weekly visual inspections and daily data inspection to assess gassing/bulging issues and to ensure that testing stops prior to rupture of the pouch cell. A recent publication provided many useful recommendations on the details of safe testing on batteries.[37]

3.3 After cell test

Cycled Li metal pouch cells contain large amount of pulverized Li particles. Without bonding Li particles together, cautions need to be taken when handling the cells. Sometimes it is necessary to disassemble the high-energy cells for further analysis, then the end-of-life status of the cell needs to be checked first, i.e., in the charged or discharged status and open circuit voltage. If the cycled cell is in the charged state, a very slow rate of 0.05 C can be used to discharge the cell to the lower cutoff voltage to release the energy from the cell.

Cell transfer: Cycled Li metal pouch cell needs to be taken out from the testing chamber for either disposal or further analysis in the glovebox. Because cycled pouch cells have pulverized Li particles, specific safety steps need to be taken when transferring the cycled cells. Figure 8 shows an exemplary procedure for transferring the cycled Li metal pouch cells into a glovebox with the aid of personal protective equipment, including safety goggle, face mask, fire-resistant lab coat, and heat-resistant gloves. Ready-to-use Lith-X or sand extinguisher should also be around. IR camera and battery safe container can also be used to enhance safety when transferring cells. When transferring cells at least two researchers should be present. During transfer and disassembly described below, 100% guarding of the cell terminals should occur to prevent inadvertent external shorting of the cell.

Cell disassembly: As with the transfer step, cell disassembly should only occur when multiple researchers are present in the laboratory. To mitigate the risks associated with the disassembly of cycled Li metal pouch cells, an integrated safety toolbox has been built (Figure 9). The safety toolbox for disassembling the cycled cell include 1) Shield, which provides additional protection in the incident of cell failure; 2) IR camera, which tracks the temperature change during the whole disassembly process. Stop work and pour Lith-x powder on Li metal or sands on the battery if temperature increases to above 50°C; 3) Heat-resistant gloves, which help to protect the glove (and hand) in case of thermal runaway; 4) Insulated container with a heat-resistant silicon mat placed inside. The silicon mat collects the wastes as well as the Lith-X powder if applied. It also avoids the direct contact of cell wastes with the metal benchtop of the glovebox; 5) The Kapton tape applied to fix the location of the tab as discussed earlier, will facilitate the disassembly process; 6) Tweezer with ceramic tips should be used for grabbing the cell; 7) Ceramic-coated scissor or ceramic scalpel used to cut the packaging bag and tab of the cell; 8) Waste container for Li metal; 9) Waste container for cathode; 10) Immediate access to Lith-X extinguisher; 11) Personal protective equipment, e.g., fire-retardant lab coat. A detailed disassembly procedure of the cycled Li metal pouch cell using this safety toolbox is illustrated in Figure 10 and Experimental section. This procedure is only an example to reduce the potential risks when disassembling high-energy Li metal batteries which will greatly reduce the unnecessary incidents.

After finishing the cell disassembly, the Li metal waste is required to be stored in an Ar-filled glovebox. Filling mineral oil into the waste container for Li metal if the Li metal waste reaches 2/3 of the volume of the container (Figure 11), then the waste is ready for disposal by EH&S (Environment, health and safety).

The key points mentioned in this work can be found in Table 2 discussed earlier, which provides a quick reference for doing research on high-energy lithium metal batteries. The proposed safety practice in Table 2 only represents our own current experiences and understanding that will be continuously updated and shared with the research community. All the discussion in this work is only for research purpose and has not been certified or approved by any official institution.

4. Conclusions

Safety practices to mitigate and eliminate potential risks in the research of rechargeable lithium metal batteries have been discussed in this article. The root causes of cell short circuit have been analyzed from different aspects. Possible scenarios that may raise safety concern have been considered and discussed through the entire research cycle of high-energy lithium metal batteries. Accordingly, safety plan has been proposed for each stage of research and only used as best practice for research purpose. Most of the suggested safety procedures are also applicable to Li-ion batteries research, where the underlying causes of cell shorting are very similar. It is worth noting that the safety procedures proposed in this article should not be considered as a standard protocol for handling rechargeable Li metal batteries, but rather a summary of the knowledge gathered during the early stage of research on rechargeable Li metal batteries and subject to further modifications. It is believed that when the safety plan is strictly followed, safety risk will be minimized or eliminated when doing research on realistic high energy batteries thus accelerating research innovation for realistic batteries.

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AUTHOR CONTRIBUTIONS

J. X. initiated this safety protocol article; J. X., B. W. and Y. Y. drafted the manuscript; B. W. and Y. Y. contributed equally to this work; all authors contributed to the experimental research, data collection, discussion and revision of the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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FIGURES

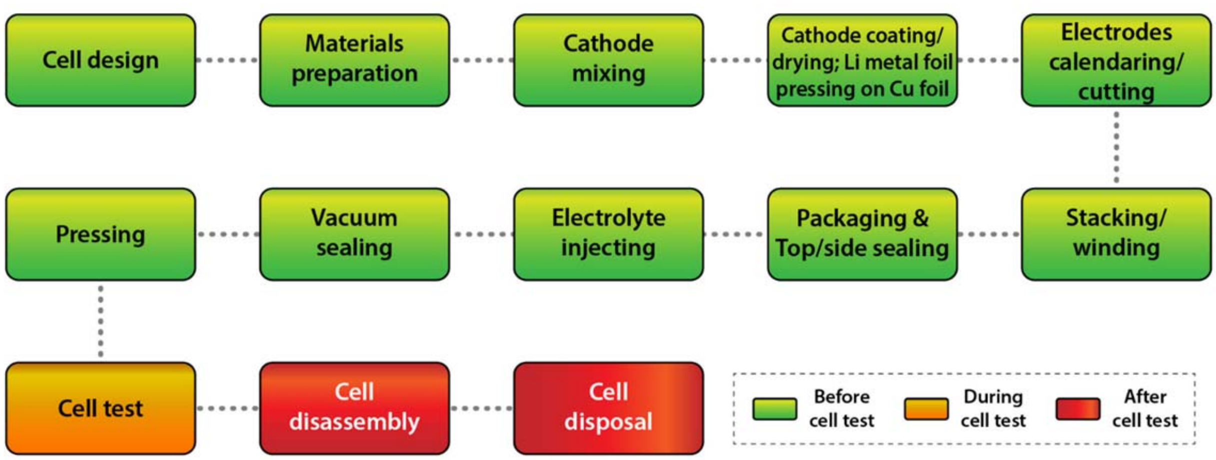


Figure 1. Flowchart of simplified research cycle for Li metal pouch cells in the lab.

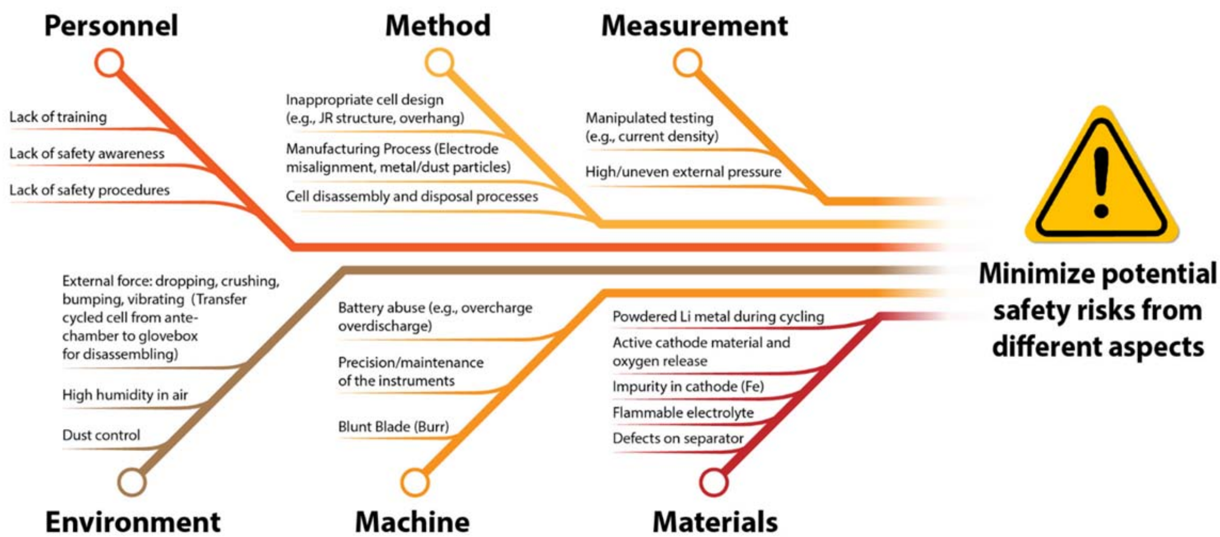


Figure 2. The fishbone diagram shows the main causes of all six aspects of root cause analysis of the safety threats of Li metal pouch cells in the laboratory, namely, personnel, machine, material, method, measurement, and environment.

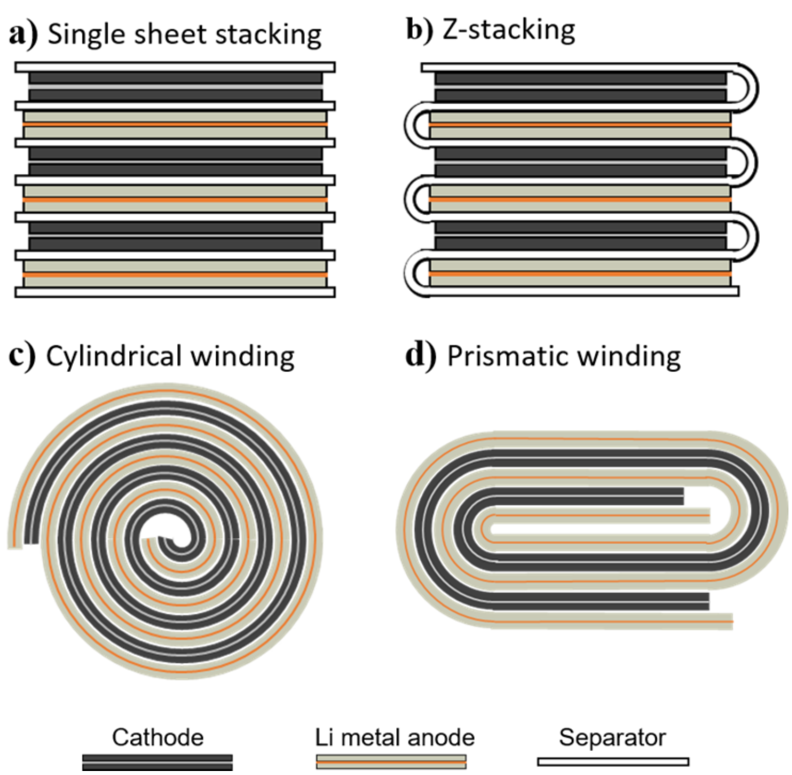


Figure 3. Schematic showing four typical types of Li metal batteries manufacturing processes. (a) Single sheet stacking; (b) Z-stacking; (c) cylindrical winding and (d) prismatic winding.

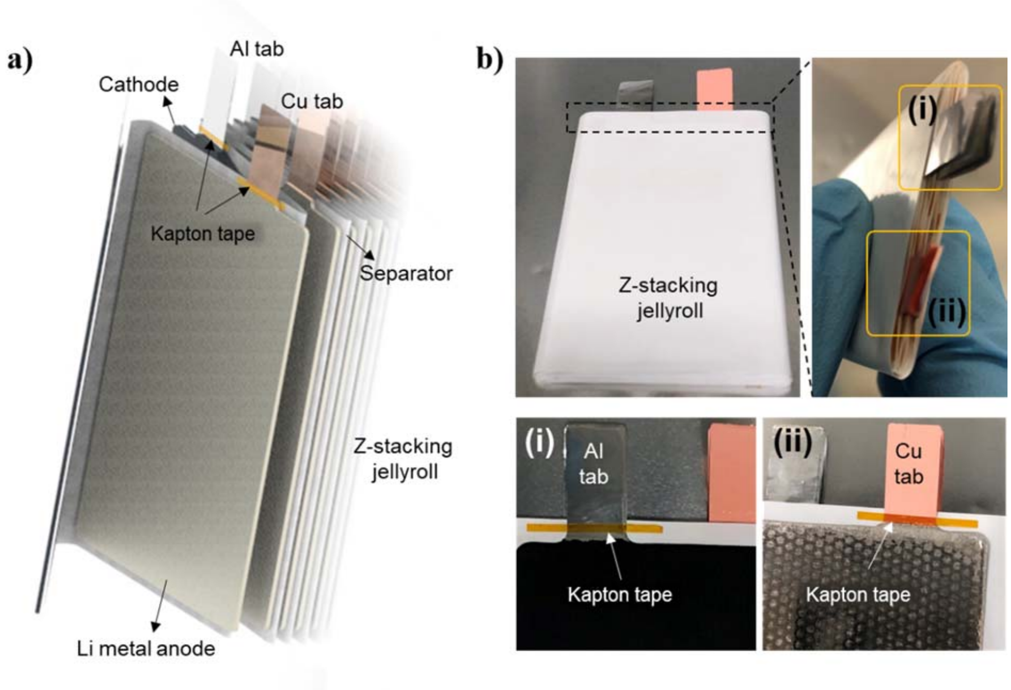


Figure 4. Kapton tape-assisted Z-stacking cell for enhanced safety. (a) Schematic of Kapton tape-assisted design in a single stacking cell unit. When stacking electrodes manually, it is suggested that each tab of the electrode is attached to the separator simply by using a small piece of Kapton tape. (b) Jelly roll included in this Kapton tape design. 1.6 cm (L) × 1 mm (W) of Kapton tapes are used to fix the position of Al or Cu tabs on overhang part (2 mm) of separator.

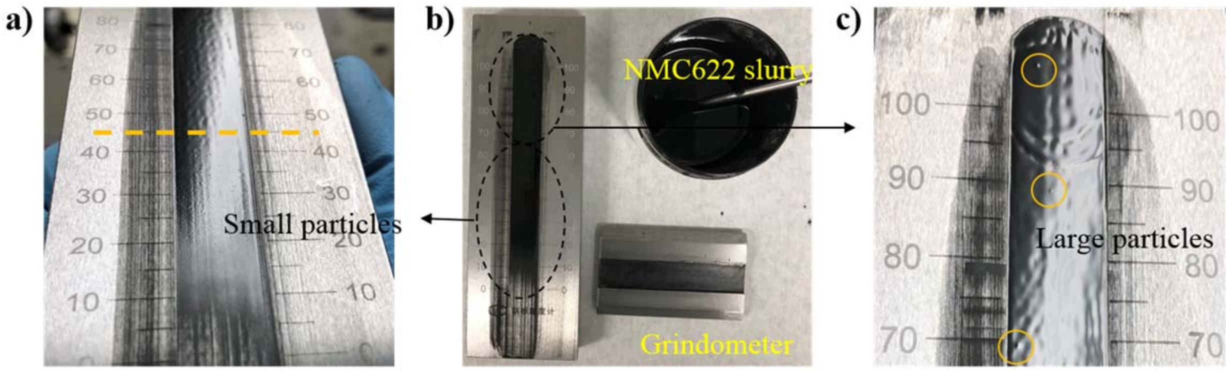


Figure 5. Digital photos of particle distribution in the NMC622 slurry inspected by a grindometer (b) and its enlarged pictures of (a) 0-80 μm and (c) 70-100 μm.

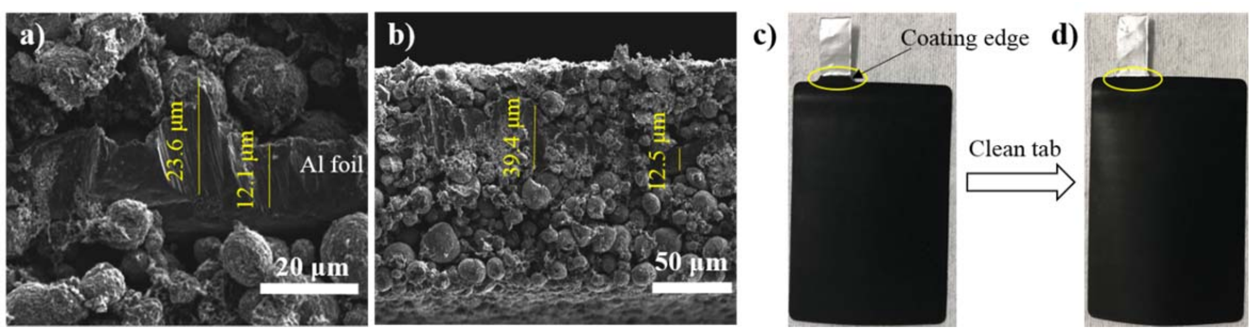


Figure 6. Burrs and particle "dusts" on the edges of electrodes due to the cutting process can affect safety. (a) Cross-sectional SEM images of NMC622 electrode cut by a cutting machine and (b) a scissor. (c) Digital photographs of NMC622 electrode before tab clean and (d) after tab clean. Cotton swab wetted by N-Methyl-2-pyrrolidone (NMP) was used to remove extra material on the tab. The thickness of Al foil is 12 μm.

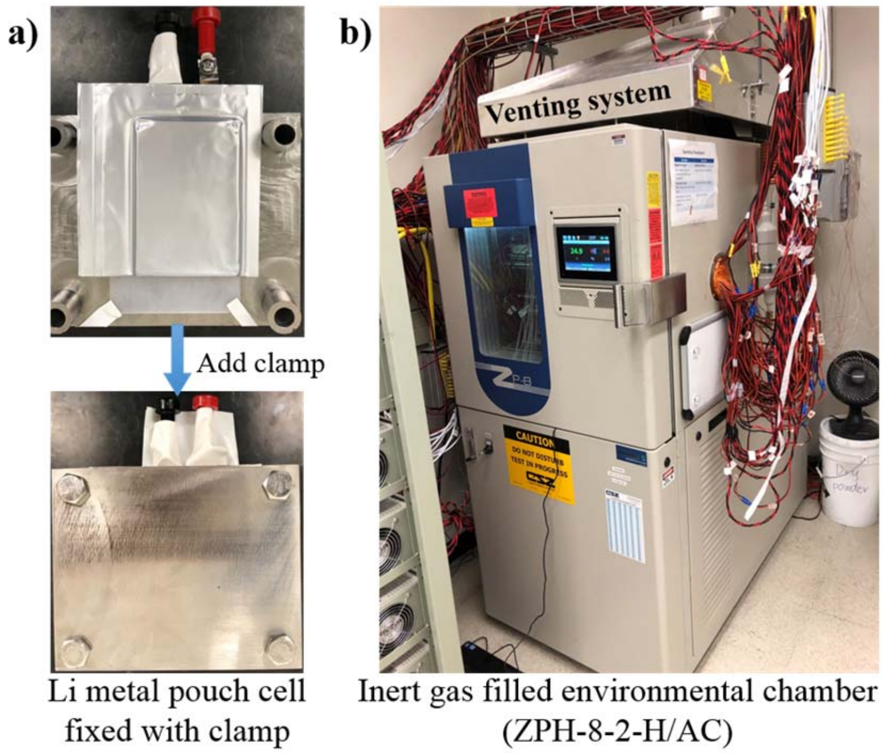


Figure 7. Strategies to help enhance safety during cell testing. (a) A stainless-steel clamping device will apply appropriate pressure on the pouch cell during testing and facilitate the heat dissipation during discharge. (b) A safety chamber filled with inert gas with a venting system will greatly reduce the risks in case of any incidents. Detailed procedures and materials for fabricating and testing NMC622/Li metal pouch cell are available from a recent report by our group.[6]

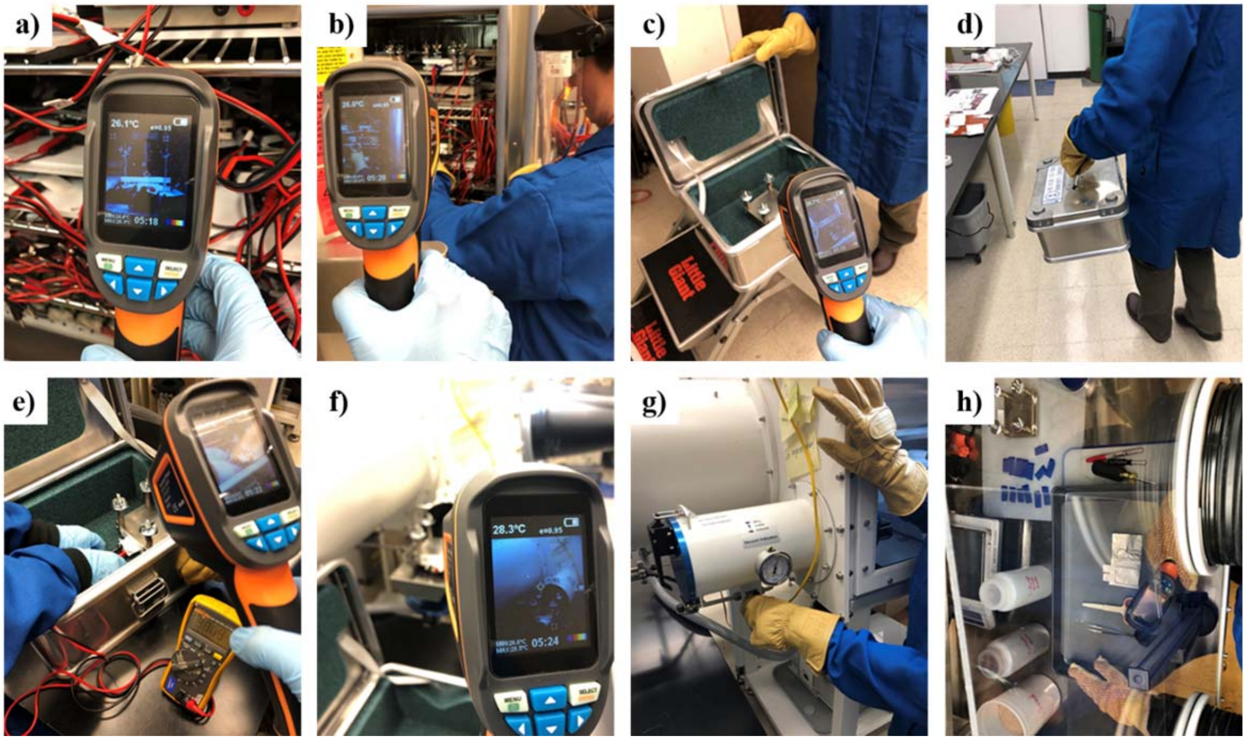
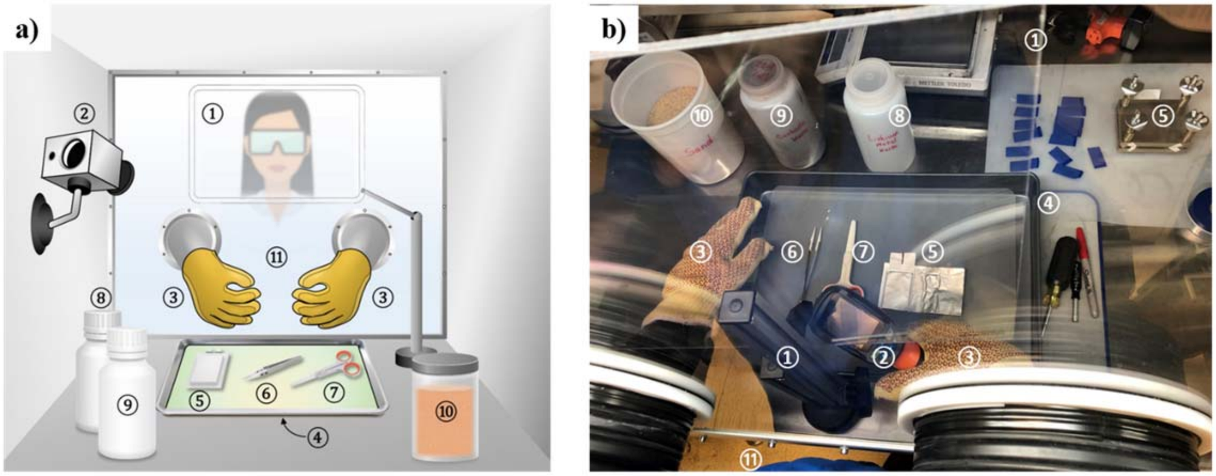


Figure 8. Suggested procedure for transferring cycled Li metal pouch cell to Ar-filled glovebox with the aid of protective equipment. (a) Open test chamber and check the temperature of the failed cell with an IR camera. (b) Personnel equipped with PPEs disconnects the failed cell. (c) Place cell in a battery safe container. (d) Transport the battery safe container to a glovebox. (e) Open the case and test the cell voltage. (f) Place the cell into the antechamber of the glovebox. (g) Evacuate the antechamber with controlled pressure. (h) Transfer the cycled pouch cell into the glovebox. It’s necessary to track the temperature through the IR camera during the whole process.



① Shield ② IR camera ③ Heat-resistant gloves ④ Insulated oven tray with heat-resistant silicon mat on bottom
⑤ Cycled Li metal pouch cell ⑥ Tweezer with ceramic tips ⑦ Ceramic scissor ⑧ Waste container for Li metal
⑨Waste container for cathode ⑩ Container for sand/Lith-x
⑪ Personal protective equipment (safety goggle, face mask, fire-resistant lab coat and heat-resistant gloves)

Figure 9. An integrated safety toolbox built to reduce the potential risks when disassembling high-energy Li metal pouch cells. (a) Schematic of the integrated safety toolbox for disassembling cycled Li metal pouch cells in Ar-filled glovebox (view from inside glovebox) and (b) Digital photograph of (a) in the glovebox (view from outside of the glovebox).

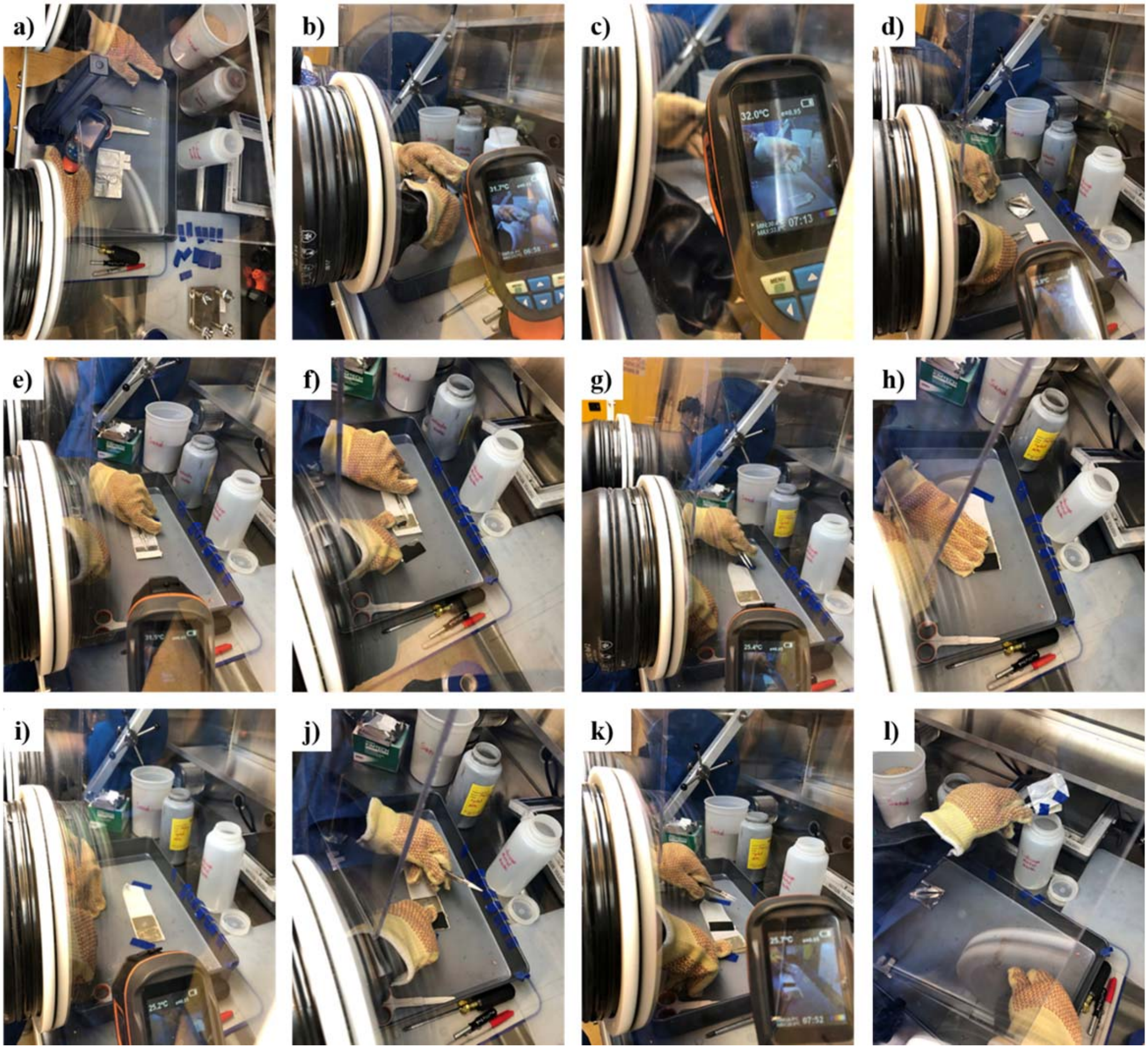


Figure 10. An exemplary procedure for disassembling cycled Li metal battery using the integrated safety toolbox described in Figure 9. (a) Ensure all the safety tools are in place. (b) Unclamp the cycled Li metal pouch cell. (c) Cut off the “gas bag” (The “gas bag” is the extra empty space of packing foil reserved for potential gas generation during formation of SEI film (solid electrolyte interface). It is internally connected to the pouch cell, see item ⑤ in Figure 9b). (d) Cut off the two tabs and take out the jelly roll. (e) Remove the tape on the jelly roll and unwrap the separator. (f) Peel off the first cathode sheet. (g) Put the cathode sheet and residues in

the cathode waste container. (h) Turn over one single cell unit (Separator/Li/Separator/NMC622) like opening a page of the book. (i) Remove the second cathode sheet and tape a corner of the separator/Li metal/separator to fix the JR on the mat. (j) Repeat step H and I to continue to disassemble the second single cell unit. (k) Repeat step H and I to continue to disassemble the cell till the last piece of cathode sheet. (l) Put cycled Li metal sheet wrapped by the separator into the Li metal waste container. The whole disassembly process of the cycled cell should be tracked by an IR camera.

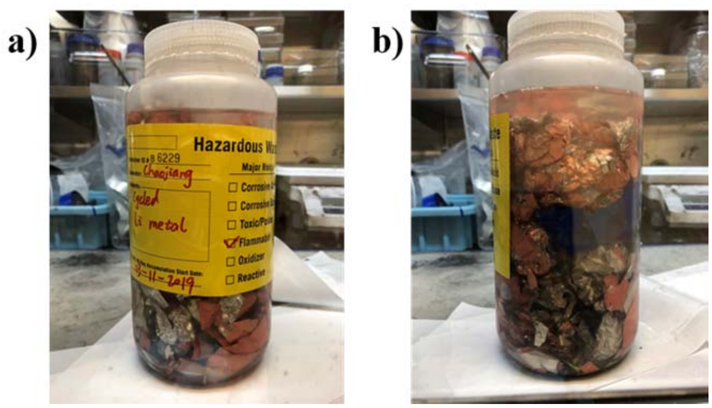


Figure 11. The container for Li metal waste should be filled with mineral oil if the Li metal waste reaches 2/3 of the volume of the container. (a) Front side and (b) back side of the waste container for Li metal filled with mineral oil.

TABLES

Table 1. Comparison of physical properties of several separators.[30]

Separator	Material	Thickness (µm)	Porosity (%)	Tensile strength* (Kgf/cm^2)		Puncture strength (gf)	Heat shrinkage /hour @ 105°C (%)	
				TD	**MD**		TD	MD
Celgard®2500	PP	25	55	135	1055	335	0	2.97
Celgard®2325	PP/PE/PP	25	39	150	1750	380	0	2.21
Targray®PP20	PP	20±2	42±2	/	≥1100	≥300	≤1	≤3
Targray®PE20A	PE	20±2	45±5	≥1200	≥1200	≥500	≤3	≤5
Targray® PE22	Ceramic coated PE (double side)	16±3	45±5	≥1700	≥1700	≥500	≤1	≤1

*TD stands for transverse direction, MD stands for machine direction, kgf/cm^2 stands for kilogram-force per centimeter square and gf means gram force.

Table 2. Summary of some key safety practices on handling high energy Li metal pouch cell.

Status	Possible Hazards	Hazard Level	Actions
Before cell test	Assembling process (burr, metal, dust, high-humidity, etc.)	Low	1) Always wear the flame-retardant lab coat, protective mask and gloves. 2) Use Hi-pot tester to screen the bad dry cells. 3) After assembling the pouch cell, attach insulated rubber tape on metal tabs. 4) Aging for two days in the safety chamber to check: electrolyte leaking, voltage stability, gas generation, etc.
During cell test	Li metal pulverization	High	1) Li metal pouch cell must be tested in a safety chamber filled with inert gas. 2) The pouch cell is sandwiched between fire retardant foams and being clamped to keep uniform pressure. 3) Place the pouch cell horizontally. 4) Avoid fast charging, using C/10 or lower current densities at the early research stage. 5) Set capacity and voltage protection. 6) Frequent check on the pouch cell during testing.
	Fast charging	Medium	
	Overcharging	High	
After cell test	Li metal “powder”	High	1) Lith-X dry powder and silicone oil must be ready in place. 2) After testing, rest the cycled cell for two additional days in the safety chamber. 3) Before opening the safety chamber, make sure staff members wear the fire-retardant lab coat, protective mask and gloves. 4) Never disassemble the clamp outside the glovebox. Transfer the whole clamp (together with pouch cell) into the glovebox directly, evacuate to -0.5 bar for more than 10 times in the antechamber. 5) After being transferred into the glovebox, the pouch cell can be taken out of the clamp. 6) Use ceramic scissors to cut the packaging foil on top of a non-flammable blanket. 7) Sort the cathode, separator, Li metal anode and packing foil, and store them in individual containers. 8) Collect all the Li anode metal material (powder or residual foil) into the waste Li container, then fill the container with silicon oil. 9) After disassembling the cell, clean scissors, tweezers, etc. that are touched by Li. Kim Wipes and any paper tissues that are contaminated by Li POWDERS need to be stored in waste containers filled by silicon oil. 10) In case of flashes or fire, spread sands (Lith-X dry
	Vibration during cell transfer	High	
	Easily short during disassembling the cell	High	
	Residual Li powders easily catch fire	High	

			powder) onto failed cell or drop the whole cell into the water tank (if outside the glovebox).